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Strategies for monitoring tropical deforestation using satellite data

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Abstract. Measuring the aerial extent of tropical deforestation for other than localized areas requires the use of satellite data. We present evidence to show that an accurate determination of tropical deforestation is very difficult to achieve by a 'random sampling' analysis of Landsat or similar high spatial resolution data unless a very high percentage of the area to be studied is sampled. In order to achieve a Landsat-derived deforestation estimate within ±20% of the actual deforestation amount 90% of the time, 37 of 40 scenes, 55 of 61 scenes and 37 of 45 scenes were required for Bolivia, Colombia and Peru respectively.

1. Introduction

There is much interest in the extent of tropical forests and their rates of deforestation for two reasons: greenhouse gas contributions and the impact of profoundly negative biodiversity. Deforestation increases atmospheric CO_2 and other trace gases, possibly affecting climate, because the concentration of carbon is higher in forests than in the agricultural lands which replace them (Woodwell *et al.* 1983, Houghton and Skole 1990, Gash and Shuttleworth 1991, Houghton 1991, Houghton *et al.* 1991, Keller *et al.* 1991, Dixon *et al.* 1994, Fearnside 1996).

Tropical forests occupy less than 7% of the terrestrial surface yet contain more than half of all plant and animal species (Raven 1988, Myers 1992). Tropical deforestation is responsible for massive species extinction and affects biological diversity in three ways: habitat destruction, isolation of formerly contiguous forest into forest fragments, and adverse physical and biological consequences of edge and 'buffer' effects within a boundary zone between forest and deforested areas (Prance 1982, Pimm *et al.* 1995).

Global estimates of tropical deforestation vary widely and range from ~50 000 to 170 000 km^2 y^{-1} (Myers 1980, 1991, 1992, FAO/UNEP 1981, Lanly 1982, Houghton 1991, FAO 1993, Grainger 1996). Recent FAO tropical deforestation estimates for 1990–1995 cite 116 756 km^2 y^{-1} globally, with 47 000 km^2 y^{-1} attributed to tropical South America—the majority of that in Brazil (FAO 1996) (table 1).

Skole and Tucker (1993), Skole *et al.* (1994) and INPE (1999) have reported lower deforestation rates for the Amazon Basin of Brazil than had been previously assumed, although there was an acceleration of the deforestation rate in 1995–1997 (INPE 1999). With a convergence of tropical deforestation estimates from

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Table 1. Summary of the Food and Agricultural Organization of the United Nations estimates for South America total forest cover and annual deforestation for 1980–1990 (FAO 1992) and 1990–1995 (FAO 1996). FAO (1996) reports a standard error of ± 4% for their estimates of mean total forest cover and a standard error of ± 12–14% of mean annual deforestation rates.

Country	1980 Total forest cover (km^2)	Annual deforestation rate 1980–1990 ($km^2\ y^{-1}$)	Annual deforestation rate 1990–1995 ($km^2\ y^{-1}$)
Bolivia	493 170	6 250	5 810
Brazil	5 611 070	36 710	25 540
Colombia	540 064	3 670	2 620
Ecuador	119 620	2 380	1 890
French Guyana	199 970	0	10
Guyana	184 160	180	90
Paraguay	128 590	4 030	3 270
Peru	679 060	2 710	2 170
Surinam	147 680	130	120
Venezuela	456 900	5 990	5 030
Total	9 160 284	62 050	46 550

Brazil, attention has focused on tropical forests elsewhere in South America, where deforestation rates are unknown or disputed.

Satellite technology is required for the determination of tropical deforestation due to the inaccessibility of many areas and the impracticability of aircraft-based survey methods. Two principal types of satellite data have been used to produce estimates of tropical deforestation: 1 km data from the Advanced Very High Resolution Radiometer (AVHRR) (Tucker *et al.* 1984, Malingreau and Tucker 1988, Malingreau *et al.* 1989, 1995, Cross *et al.* 1991, Moran *et al.* 1994, Mayaux and Lambin 1995, 1997, Stone *et al.* 1994, Mayaux *et al.* 1998) and Landsat data using the 80 m Multi-Spectral Scanner (MSS) and 30 m Thematic Mapper (TM) instruments (Tardin *et al.* 1979, 1980, Skole and Tucker 1993, Chowmentowski *et al.* 1994, Skole *et al.* 1994, Townshend *et al.* 1995).

Imaging radar has been suggested as a possible satellite data source for mapping tropical forest extent and deforestation. The application of satellite radar data to tropical forest inventory has, however, been limited because multiple polarizations and multiple acquisition(s) are required. For example, C-band radar data have been found to be of limited use for mapping deforestation, while multiple polarizations of L-band radar are required to obtain an accurate mapping of deforested tropical areas (Rigot *et al.* 1997).

While some researchers feel limitations abound regarding accuracy and mapping consistency of tropical forest extent and deforestation (Downton 1995), it is our opinion that high deforestation accuracies have been achieved. The procedures we have adopted have achieved high accuracies through a combination of the use of high-resolution satellite data, integration of automated methods and human interpreters, and the extensive involvement of experts from the regions concerned (Townshend *et al.* 1995).

Estimation of deforestation rates has to take account of the fact that tropical deforestation does not occur uniformly across a region or country. Instead, it is usually concentrated in a relatively small fraction of the area of interest (Fearnside

1986, Skole and Tucker 1993, Skole *et al.* 1994, Stone *et al.* 1994). Furthermore, knowledge of such 'hot spots' of deforestation is at times poor, especially as new hot spots develop.

In this paper we examine deforestation estimates using Landsat-based sampling strategies. We extend the work of Sanchez *et al.* (1997) who demonstrated the inadequacy of conventional random sampling methods for Brazil. We carry out related simulations for Bolivia, Peru and Colombia and assess the implications of errors in deforestation and forest cover estimation.

2. Impact of sampling strategies on estimation of deforestation rates

Landsat data were used to determine the extent of tropical deforestation using 'wall-to-wall' data from the MSS and TM instruments (Skole and Tucker 1993, Skole *et al.* 1994, Tardin *et al.* 1979, 1980, INPE 1999). This type of analysis is usually too expensive for many investigators and the analysis of randomly selected Landsat scenes has been suggested as an alternative to wall-to-wall studies (FAO 1993, 1996).

The University of Maryland's Landsat Pathfinder Tropical Forest Project has been analysing satellite data from the non-Brazilian Amazon of South America (Townshend *et al.* 1995). A wall-to-wall analysis of digital satellite data from the mid-1970s, mid-1980s, and early 1990s was attempted. In practice, 50% cloud-free coverage for the 1970s, $>90\%$ for the 1980s, and $>90\%$ for the 1990s was achieved. A total of 200 scenes were analysed for the mid-1980s and early 1990s covering Bolivia, Peru, Columbia, Ecuador and Venezuela.

A hybrid procedure integrating automated methods with an intensive human editing phase was used. Unsupervised classification first identified the principal cover types. Although this achieved an accuracy of more than 85%, errors arose from atmospheric haze, cloud shadow and spectral–spatial–phenological confusion among many classes. However, trained interpreters were able to eliminate most of the errors resulting from these problems. Extensive field checking and advice from in-country experts was also included (Townshend *et al.* 1995).

We used actual results of our Landsat wall-to-wall deforestation analysis and coupled them with a computer simulation program to determine how well we could estimate deforestation using random sampling of Landsat images. We randomly sampled complete Landsat images rather than randomly sampling small areas within the area of interest. We did this because the smallest unit of Landsat data that can usually be purchased is a complete Landsat scene. Hence a sampling strategy based on sampling smaller units would save little or nothing in acquisition costs. In the FAO procedure (FAO 1996) Landsat scenes were randomly selected and then sample areas within the scenes themselves selected. Clearly, our procedure of randomly selecting scenes and using the figures for the whole of the scenes will result in smaller standard errors than any method based on samples within these scenes.

For each sampling determination, 200 trials were run, starting with two randomly selected scenes and incrementing step-by-step up to the total number of Landsat scenes for the country or region under study. Each scene could only be used once. We determined the number of times our randomly sampled estimate, extrapolated to the country or region under study, was within $\pm 10\%$, $\pm 20\%$ and $\pm 50\%$ of the actual wall-to-wall deforestation total (table 2). Three methods were used to

Table 2. Sample simulation output for three randomly selected Landsat scenes from the 40 total scenes studied for Bolivia for 1985–1986 and 1992–1993. This example is for three randomly selected Landsat images (scenes 5, 15 and 26). Note the range of deforestation estimates which result from using the total area, the total forest area, and the previous 1985–1986 deforestation amount. Simulations like these were performed 200 times on order to evaluate the number of scenes (from 2 to 40) needed to achieve the 'target' estimation of deforestation.

	Path/Row	Total area (km^2)	Total forest (km^2)	Total 1993 deforestation (km^2)	Total 1985 deforestation (km^2)	Total 1985 deforestation by these scenes (%)
Scene 5	230/73	26 236	6 240	1 334	693	4.2%
Scene 15	232/70	26 569	6 746	144	144	0.8%
Scene 26	232/69	24 770	6 801	1 013	18	0.1%
Total for the three scenes:		**77 575**	**19 787**	**2 491**	**855**	**5.1%**
Total area of Bolivia studied (km^2):				784 759		
Total forest area of Bolivia studied (km^2):				433 980		
Total deforestation from Bolivia (km^2):				28 208		
						Three-scene scaled deforestation estimate (km^2)
Total area scaling: 784 759/77 575 × 2491 =						**25 209**
Forest area scaling: 433 980/19 787 × 2491 =						**54 627**
1985 actual deforestation scaling: 100%/5.1% × 2491 =						**48 849**
			Lower limit	Upper limit		
Plus/minus 10% of 28 208:			25 389	31 031		
Plus/minus 20% of 28 208:			22 568	33 852		
Plus/minus 50% of 28 208:			14 105	42 315		

extrapolate the randomly selected deforestation estimate to the area of the country or region studied:

(1) (total area under study) ÷ (total area of random sample);
(2) (total forest area under study) ÷ (forest area of random sample);
(3) the sample using the preceding period's deforestation contribution for the Landsat scenes to scale the values for the entire country (see table 3). This approach can only be used in areas which are cloud-free among/between measurement periods.

In table 2 the calculations used to make these three estimates are shown in detail for Bolivia, where three scenes were used to calculate the deforestation estimates. The 1992–1994 lowland Bolivia deforestation totalled 28 208 km^2, the total area studied was 784 759 km^2, and the total forest area was 433 980 km^2. The distribution of deforestation and forest cover is shown in table 4.

The combined 1985–1986 results for Bolivia, Colombia and Peru with this simulation indicated that a sampling procedure reliant on randomly selecting Landsat scenes and then sampling within them will likely give quite poor estimates of actual deforestation (figure 1).

As a summary of the results presented in figure 1, we can use the estimation metric achieving the specified estimation error range 90% of the time. To achieve an estimate within ± 20% of the actual deforestation value would require the analysis of 35 Landsat scenes for Bolivia, 55 for Colombia, 37 for Peru, and 105 for the combined Bolivia–Colombia–Peru area (figure 1 and table 3). Thus it is necessary to randomly sample 70–90% of the total area in question to obtain a ± 20% estimate of deforestation 90% of the time. A random sampling deforestation estimation effort with a high accuracy expectation actually means almost a complete wall-to-wall analysis in practice (table 3).

Figure 1 and tables 2 and 3 show that deforestation estimation via a Landsat image random sampling technique is highly inaccurate for Bolivia, Colombia and Peru. As a possible alternative, several changes in the random sampling strategy were investigated. These included restricting the area upon which the sampling is based to only the forested area and including previous deforestation information in later estimates. These approaches were evaluated for our Bolivian 1985–1986 and 1992–1994 deforestation results (figure 2).

Table 3. Summary of the average number of randomly selected Landsat scenes for Bolivia, Colombia and Peru to achieve a deforestation estimate for each country within ± 50%, ± 20% and ± 10% of the actual deforestation 90% of the time, as determined from the UMD 1985–1986 wall-to-wall analysis (see also figure 1).

	Number of Landsat scenes for country or area	Average number of scenes needed to be within x of actual deforestation 90% of the time		
		$x = \pm 50\%$	$x = \pm 20\%$	$x = \pm 10\%$
Bolivia	41	24	35	37
Colombia	61	40	55	57
Peru	45	20	37	41
Bolivia–Peru–Colombia	147	45	105	135

Table 4. University of Maryland Landsat Tropical Forest Pathfinder Project results for lowland Bolivia for 1985–1986. A total of 41 individual Landsat MSS and TM images were digitally classified, vectorized, incorporated into a geographic information system, edited, registered and merged into a seamless data set for lowland Bolivia.

WRS Path	WRS Row	Total forest cover (km^2)	Total deforestation (km^2)	Deforestation of total (%)	Cumulative deformation (%)	Total water (km^2)	Total cloud (km^2)	Total non-forest (km^2)	Tile area (no overlap) (km^2)
231	72	15811	6542	39.9	39.9	433	25	3619	26430
230	72	21327	2025	12.3	52.2	232	0	2607	26191
232	72	12465	1927	11.7	64.0	453	124	10856	25825
1	71	11903	1161	7.1	71.0	937	1605	11006	26613
230	73	6880	693	4.2	75.3	330	0	18332	26236
1	68	22533	560	3.4	78.7	705	0	3370	27168
231	71	21236	525	3.2	81.9	464	8	4608	26841
233	71	22008	370	2.3	84.1	56	2021	2152	26606
2	68	19073	334	2.0	86.2	147	0	504	20058
230	71	22157	329	2.0	88.2	10	0	4078	26574
233	68	15570	311	1.9	90.1	509	0	4124	20515
1	70	20457	311	1.9	91.9	597	1156	4264	26785
229	72	21442	189	1.2	93.1	63	3	4521	26218
229	71	10552	179	1.1	94.2	48	0	6294	17073
232	70	6746	144	0.9	95.1	959	0	18719	26569
233	67	7623	133	0.8	95.9	278	0	361	8394
233	72	1973	118	0.7	96.6	177	1240	22932	26439
231	73	8067	92	0.6	97.2	134	0	17702	25995
233	70	7709	92	0.6	97.7	379	1	18877	27057
1	67	13223	83	0.5	98.2	47	1078	122	14553
231	70	21836	74	0.5	98.7	289	0	4692	26891
230	70	23555	62	0.4	99.1	16	23	3212	26867
227	73	7113	28	0.2	99.2	118	0	7929	15188
232	71	11762	27	0.2	99.4	1010	5	13436	26241
228	72	18267	18	0.1	99.5	36	275	6534	25130
232	69	7796	18	0.1	99.6	629	0	16327	24770
233	69	4212	13	0.1	99.7	1660	1	20788	26674
228	71	1817	13	0.1	99.8	25	0	2903	4757
230	69	2836	11	0.1	99.8	84	0	691	3623
2	67	1364	10	0.1	99.9	0	0	0	1374
1	69	12594	8	0.0	99.9	414	564	13029	26609
2	69	8764	4	0.0	100.0	135	303	2239	11446
227	72	3562	3	0.0	100.0	183	259	783	4790
3	68	644	2	0.0	100.0	5	0	0	651
2	70	4234	1	0.0	100.0	42	4037	2158	10471
231	69	9613	0	0.0	100.0	253	434	4846	15146
229	70	3794	0	0.0	100.0	3	3	1471	5272
228	73	9069	0	0.0	100.0	0	0	14103	23173
229	73	4005	0	0.0	100.0	1	0	21257	25263
232	68	186	0	0.0	100.0	36	0	51	273
232	73	0	0	0.0	100.0	2	0	2009	2011
Total		445778	16410			11899	13166	297507	784759

Area outside of tiles = 5225 km^2 **Study area** = 789818 km^2

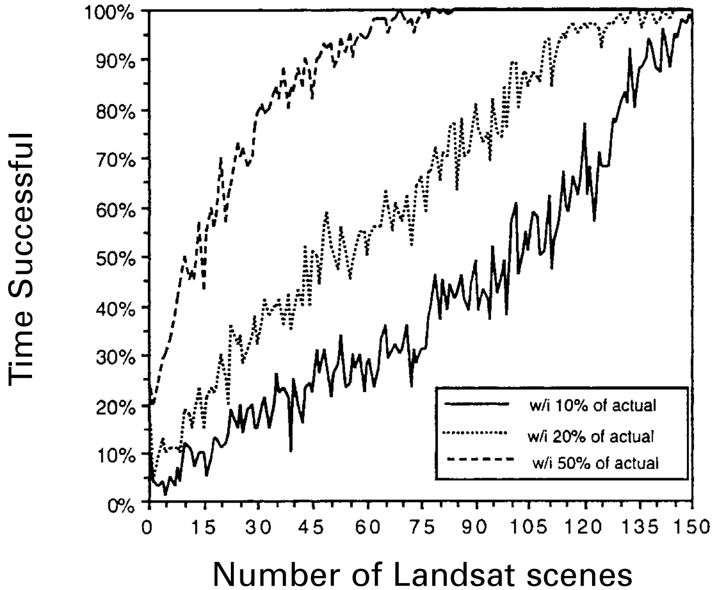

Figure 1. Summary of deforestation estimation accuracy for Bolivia, Colombia and Peru using random Landsat scene selection for a total area of 2 758 000 km^2 covered in 150 full or partial Landsat scenes. Two hundred trials were performed starting with 1 and continuing until 100% of the area or 150 Landsat scenes had been sampled. For example, the average deforestation estimation accuracy of 200 trials using 30 randomly selected Landsat scenes from Bolivia, Colombia and Peru resulted in the following: 16% of the time the deforestation estimate was within ± 10% the actual deforestation; 30% of the time the deforestation estimate was within ± 20% the actual deforestation; and 70% of the time the deforestation estimate was within ± 50% the actual deforestation.

Only a slight improvement (< 5%) was obtained for Bolivia, Colombia and Peru, individually and collectively, using the forest area method of scaling the randomly sampled deforestation estimates (see also table 3). We interpret this to reflect a similar distribution among the Landsat scenes for forest and non-forest.

We next evaluated the use of a previous time period's deforestation level as a means to extrapolate a later period sample's deforestation to the country or region under study. Because of more serious cloud cover obstruction for Colombia and Peru in the 1980s, this portion of our study was restricted to Bolivia.

The basis for this approach has been outlined by Fearnside (1986) and Sanchez *et al.* (1997) who described the tendency for spatial concentration of tropical deforestation and showed a high correlation between deforestation amounts for different time periods for the same Landsat scene paths and rows respectively. This became evident when we plotted the deforestation of Bolivia by Landsat scene for 1985–1986 and 1992–1994 (figure 3).

However, when the 1985–1986 deforestation amounts were taken into account to extrapolate the 1992–1994 sampled deforestation to the area of study for Bolivia, only a 20–30% improvement in deforestation estimation accuracy resulted (compare figures 2 and 4). For example, 90% of the time the 1992–1994 deforestation would be estimated to within ± 20% of the actual amount using 32 Landsat scenes or more; this is to be compared with sampling 37 Landsat scenes if the 1985–1986

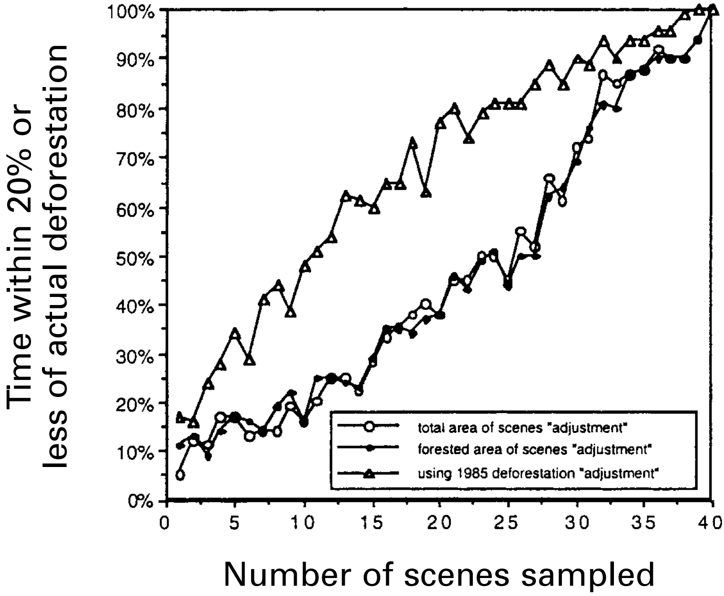

Figure 2. Comparison of simulations with 'normalization' of the random sample estimates using (1) total area of estimate, (2) forest area of estimate and (3) 1985 deforestation percentage of estimate, all with the acceptance criteria of the randomly sampled deforestation estimate being ± 20% of actual deforestation using 200 trials, for 1992–1994 Bolivian data.

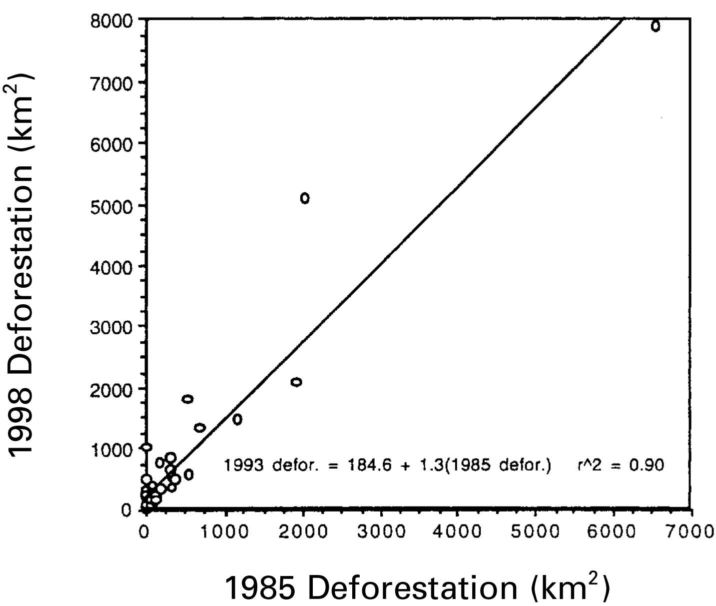

Figure 3. Plot of deforestation by Landsat scene from 1985–1986 to 1992–1994 for a wall-to-wall survey of 798 000 km^2 of lowland Bolivia.

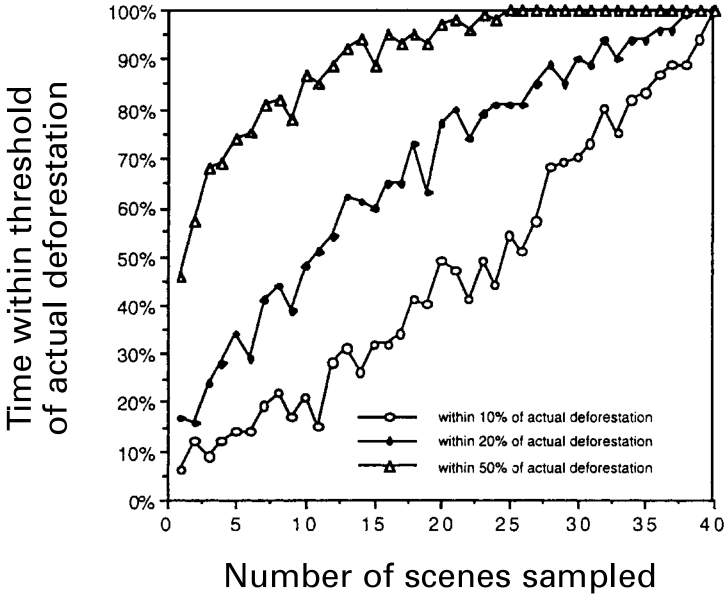

Figure 4. Comparison of simulations with acceptance criteria of ± 10%, ± 20% and ± 50% of actual deforestation using 200 trials, for 1992–1994 Bolivian data. Each random estimate of deforestation was adjusted to the entire study area based upon the 1985–1986 deforestation amount for the same area.

deforestation distribution among scenes was not taken into account. We believe that the lack of success of this procedure is due to the emergence of new hot spots of change between the time periods studied. Random sampling of tropical deforestation using Landsat or SPOT (System Probatoire pour l'Observation de la Terre) type satellite data provides inadequate estimates of actual deforestation.

3. Conclusions

We have demonstrated that wall-to-wall coverage is needed to avoid gross errors in estimations of deforestation rates. Because tropical deforestation is spatially concentrated, it is very improbable that an accurate estimate of deforestation by random sampling of Landsat scenes will be achieved. In order to achieve a deforestation estimate with an accuracy within ± 20% of the actual deforestation amount 90% of the time, 37 of 40 scenes, 55 of 61 scenes and 37 of 45 scenes were required for Bolivia, Colombia and Peru respectively. Using knowledge of the location of previous areas of deforestation, such as that suggested by Sanchez *et al.* (1997), only provided marginal improvements. Using this approach for Bolivia, a deforestation estimate with an accuracy within ± 20% of the actual deforestation amount 90% of the time required the study of 32 Landsat scenes or ~ 80% of the total area.

Alternative random sampling schemes could produce more reliable results, for example, by selecting the samples to be analysed randomly from the whole area, rather than randomly selecting whole Landsat scenes. We intend to carry out further analyses to establish whether random samples from the whole area at a 16 km grid cell size could produce better deforestation estimation results. Such a procedure would not reduce the cost of imagery acquisition but would reduce the cost of the analysis.

Our results clearly have significant implications on the advisability of methods reliant on the sampling of Landsat images, such as those formerly used by the FAO.

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